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A STOL AIRWORTHINESS INVESTIGATION USING A SIMULATION OF AN AUGMENTOR WING TRANSPORT

Volume I - Summary of Results and Airworthiness Implications

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16. Abstract

A simulator study of STOL airworthiness criteria was conducted using a model of an augmentor wing transport. This study covered the approach, flare and landing, go-around, and takeoff phases of flight. The two volumes of this report document the results of that investigation.

Volume One (NASA TM X-62,395; FAA-RD-74-179-I) summarizes the results and discusses possible implications with regard to airworthiness criteria. The results provide a data base for future STOL airworthiness requirements and a preliminary indication of potential problem areas. The results are also compared to the results from an earlier simulation of the Breguet 941S. Where possible, airworthiness criteria are proposed for consideration.

Volume Two (NASA TM X-62,396; FAA-RD-74-179-II) contains a detailed description of the simulation and the data obtained. These data include performance measures, pilot commentary, and pilot ratings. This volume also contains a pilot/vehicle analysis of glide slope tracking and of the flare maneuver.

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FOREWORD

The research reported here was done under NASA Contract NAS2-7926 as part of a joint NASA/FAA program. The Contract Technical Manager was Jack E. Cayot, the NASA Project Monitor was Charles S. Hynes, and the STI Project Engineer was Robert L. Stapleford. The work was accomplished in the period from August 1973 through February 1974.

Successful completion of this project was due to the contributions and cooperation of many individuals besides the authors. Major contributions were made by Jack E. Cayot (FAA). Special thanks are due the pilots for their patience through many long simulator sessions and their many helpful suggestions. They were: John A. Carrodus (Civil Aviation Authority, United Kingdom), Bryant Chestnutt (FAA), LTC. Robert A. Chubboy (USA and FAA), Richard M. Gough (FAA), Gordon H. Hardy (NASA), Robert J. Kennedy (FAA), John Ryan (FAA), and J.P. Van Acker (Centre D'Essais en Vol, France).

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LIST OF ABBREVIATIONS

AEO	All engines operating
AOA	Angle of attack
AWJSRA	Augmentor Wing Jet STOL Research Aircraft
BLC	Boundary layer control
BR	Breguet
CAA	Civil Aviation Authority (U.K.)
CEV	Centre D'Essais en Vol (France)
CTOL	Conventional takeoff and landing
DDC	Direct drag control
DHC	de Havilland Aircraft of Canada Ltd.
DITC	Department of Industry, Trade, and Commerce (Canada)
DLC	Direct lift control
EBF	Externally blown flaps
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FSAA	Flight Simulator for Advanced Aircraft
G/S	Glide slope
IAS	Indicated airspeed
IFR	Instrument flight rules
ILS	Instrument landing system
NASA	National Aeronautics and Space Administration
OEI	One engine inoperative
POR	Pilot opinion rating
RMS	Root mean square
SAS	Stability augmentation system
STOL	Short takeoff and landing

LIST OF SYMBOLS

BW	Bandwidth
g	Acceleration due to gravity
h	Altitude
$\dot{h}$	Rate of climb (ft/sec)
n_{z_α}	Normal load factor per unit angle of attack (g/rad)
N_H	Engine RPM (% maximum)
T	Thrust (lb); transparency (BR 941S) (deg)
u	x component of velocity perturbation
V	Airspeed
V_1	Critical engine failure speed (kt)
V_2	Takeoff safety speed (kt)
V_{MCG}	Ground minimum control speed (kt)
V_{min}	Minimum possible speed at given power setting (kt), $\left.\frac{\partial\gamma}{\partial V}\right\vert_{\delta_T} = \infty$ at V_{min}
V_R	Target rotation speed (kt)
V_s	Power off stall speed (kt)
α	Angle of attack (deg)
δ_f	Flap deflection (deg)
δ_T	Throttle position
δ_ν	Nozzle position (deg)
Δ	Open loop transfer function denominator
γ	Flight path angle (deg)
θ	Pitch attitude
μ^{STOL}	Flight path/airspeed cross coupling parameter
τ	Time delay (sec)
τ_E	Engine lag (sec)
ω	Frequency (rad/sec)

SECTION I

INTRODUCTION

A. BACKGROUND

It has been widely recognized that CTOL airworthiness criteria are not generally appropriate for STOL aircraft. Therefore, the FAA has undertaken a long-range program to develop STOL airworthiness standards. Included in that program is a series of simulation experiments using models of different STOL concepts such as deflected slipstream, augmentor wing, and externally blown flap. The first series of experiments used a model of the Breguet 941S deflected slipstream STOL airplane. The results are presented in References 1 and 2. This report deals with the second such simulation, but this time using an augmentor wing STOL aircraft.

These simulations were conducted under a joint NASA/FAA program at NASA Ames Research Center on the Flight Simulator for Advanced Aircraft (FSAA). Eight subject pilots represented the FAA, NASA, CAA (United Kingdom), and CEV (France). Most of these pilots had been involved in prior simulation activities in this program, and therefore, provided considerable continuity. This was aided by conducting tests in a similar manner as before. Such things as piloting tasks, rating scheme, atmospheric disturbances, cockpit layout, etc. were similar to the earlier BR 941S tests. The only fundamental change was the particular aircraft being simulated.

The STOL airplane model used in this series of experiments was based on design data for the NASA/DITC Augmentor Wing Jet STOL Research Aircraft (AWJSRA), an extensively modified DHC-5 BUFFALO STOL airplane (not intended for use as a transport). This airplane is powered by two Rolls-Royce SPEY turbofan engines. Hot thrust is directed through nozzles which can be manually vectored continuously from horizontal to vertical. Cold thrust from the engines is ducted to augmentor flaps and fuselage and aileron BLC. The configuration used during most of this experiment consisted of a weight of 18143 kg (40,000 lb), flaps at 65 deg, and nozzles at 75 deg. This model provided the flexibility to examine simulator cases spanning a wide range of dynamics. By varying speed the basic aerodynamics could be varied. Also,

engine lags could be varied; and, by using nozzle in place of throttle, the effective thrust vector could be switched from vertical using throttle to horizontal by using nozzle.

The scope of the augmentor wing study was limited to the STOL approach and landing, go-around, and takeoff. Major emphasis was placed on longitudinal flight path control in the approach and landing since this is the area where STOL aircraft differ most from conventional aircraft. This is also where effective criteria are most lacking.

B. ORGANIZATION OF THE REPORT

This report consists of two volumes. This volume summarizes the results of the augmentor wing simulation and interprets them with regard to airworthiness criteria. Section II presents concisely stated findings along with a brief discussion and any possible implication on airworthiness standards. Section III sets forth ideas for STOL airworthiness standards based on the results of this program to date. The Appendix contains tabulations of criteria proposed by others applied to some of the cases flown in the AWJSRA and BR 941S simulations.

Details of the simulation results and analyses are presented in Volume Two. The major breakdown of Volume Two is made in terms of the four primary tasks: ILS tracking, flare and landing, go-around, and takeoff. Data acquired during the simulation are presented in the body of Volume Two with analytical methods described in the Appendices.

SECTION II

SIMULATION RESULTS

This section presents the results of the augmentor wing simulation program. These results are based on the measur d performance, pilot comments and ratings, and on the detailed analyses presented in Volume Two of this report.

Each finding is stated concisely then discussed briefly. Where applicable, related results from the earlier BR 941S simulation are included in the discussion. Following the discussion of each result, any implications on airworthiness standards are mentioned.

The results presented here generally follow the summary of Section VII, Volume Two, and similarly are separated into the following areas:

- ILS tracking
- Flare and landing
- Go-around
- Takeoff

A. ILS TRACKING

Finding: The 65 kt* baseline case was judged acceptable for the ILS tracking task.

Discussion: This case was flown by all subject pilots and was the main standard by which other cases were compared. (Detailed descriptions of this and the other cases flown are presented in the Appendices of Volume Two.)

Finding: For the baseline case (and in general) turbulence and winds had a major effect on pilot workload and performance.

* The trim airspeed was used to identify particular operating conditions for this experiment. A complete description of operating condition would also include loading, flap and nozzle deflections, and power setting.

Discussion: As an example of the effect of turbulence, the 65 kt case average pilot rating ranged from 2.9 in calm air to 4.1 in 4.5 fps RMS turbulence to 5.1 in shears and turbulence. Similar effects of turbulence were obtained in the BR 941S simulation.

Implication: Airworthiness standards will require some consideration for the levels of atmospheric disturbance in which the aircraft are expected to operate.

Finding: Decreasing approach speed (65 kt, 60 kt, 55 kt) continuously increased workload with an unacceptable level between 60 and 65 kt; performance remained unaffected for a constant level of atmospheric disturbance over a wide range of speeds.

Discussion: The unfavorable effect of decreasing approach speed was also observed during the BR 941S simulation and the reasons for the effect will be stated shortly. However, the important point to note here is the characteristic of pilots striving for a given level of performance at the cost of increased workload.

Implication: Performance measurements may be necessary but are not sufficient to describe the acceptability of a particular approach flight condition.

Finding: The flight path control characteristics were explainable in terms of bandwidth (quickness of flight path control), sensitivity (sensitivity of flight path to control movement), control power (maximum possible flight path change up and down), and cross-coupling (coupled IAS and G/S responses to attitude and power inputs).

Discussion: These measures of flight path control are fundamental to any control situation but are introduced here to provide a framework for classifying airframe configurations and flight conditions in terms of pilot acceptability. Such a scheme seems necessary because of the varied ways flight path control problems are manifested in STOL aircraft.

Implication: This classification framework could be the basis for airworthiness standards pertaining to longitudinal flight path control.

Considerable definition of limits has already been accomplished in these BR 941S and AWJSRA simulation programs as well as in numerous other efforts.

<u>Finding</u>: Decreasing approach speed affected only the IAS-G/S cross-coupling characteristic in a significant way and the effect was adverse.

<u>Discussion</u>: The search for the explanation of the undisputable degradation with decreasing approach speed ended with only one identifiable culprit: IAS-G/S cross-coupling. In reviewing the BR 941S results, a similar trend was discovered. The nature of the cross-coupling phenomenon involved is easily seen to be of a pilot-confusion factor, and thereby increasing workload. A means of quantifying cross-coupling will be discussed shortly.

<u>Implication</u>: This may be a key factor in arriving at a minimum acceptable approach speed, or more generally, a minimum acceptable level of flight path control behavior. It is important to recognize that the nature of cross-coupling is a key distinguishing characteristic between conventional and STOL aircraft.

<u>Finding</u>: Increasing the approach speed did not change the pilot workload from the level of the baseline case.

<u>Discussion</u>: Increasing approach speed beyond a certain point did not significantly change the nature of the cross-coupling or bandwidth.

<u>Implication</u>: Flap placard speeds and landing performance considerations will probably set upper approach speed limits rather than flight path dynamics.

<u>Finding</u>: Cross-coupling can exist in varying degrees depending upon how quickly the pilot is making closed-loop flight path corrections.

<u>Discussion</u>: This is an aspect of flight path control dynamics which has not been addressed to date by any proposed criteria. While a "backsidesness" limit on $\frac{\partial \gamma}{\partial V}$ is related to cross-coupling, this only involves steady-state conditions. One of the essential differences between STOL and conventional aircraft is the nature of dynamic cross-coupling. This is most directly shown by a metric such as μ^{STOL} which is frequency dependent.

Implication: An airworthiness criterion limiting dynamic cross-coupling should be considered for STOL aircraft.

Finding: A tailwind had an effect equivalent to decreasing approach speed, mainly in terms of coupling.

Discussion: In analyzing the cases flown, trim adjustments for steady winds were found to have a significant effect on the flight path dynamics. This apparently stems from the difference in trim power required to fly the same glide slope in headwinds versus tailwinds. The main effect of a headwind or tailwind component was a change in the cross-coupling. In general, a headwind had the same effect on trim as a small increase in approach speed and a tailwind had the effect of a relatively larger decrease in approach speed. Other flight path control characteristics were largely unchanged by winds.

Implication: Compliance with flight path control criteria should be demonstrated over all operational combinations of aerodynamic flight path angle* and airspeed; or over the equivalent combinations of sink rate and airspeed. This would cover limits on steady wind conditions and glide slope angle variations.

Finding: Varying the response time of the complementary control (e.g., throttle, DLC, etc.) is a way of changing flight path bandwidth (quickness) without affecting coupling or any other control characteristic.

Discussion: While varying approach speed affected primarily cross-coupling characteristics, varying engine response affected only bandwidth. Furthermore, clear trends of worsening pilot opinion were observed as this lag was increased.

Implication: This sort of variation is useful in establishing an acceptable level of bandwidth for a given set of IAS-G/S cross-coupling characteristics.

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* Aerodynamic flight path angle $= \sin^{-1}$ (altitude rate/airspeed).

Finding: Degraded complementary control response became a problem as it approached the bandwidth where the pilot was operating, which in turn was dependent on the intensity of disturbance.

Discussion: This is simply an observation that the flight path control bandwidth required depends upon the operating conditions. Probably the biggest factor in determining bandwidth requirements is the level of atmospheric disturbance expected in operation.

Implication: A bandwidth (quickness) related requirement could depend on expected levels of shears and gusts.

Finding: Use of a horizontal complementary control (e.g., nozzle, DDC) requires speed regulation in order to achieve sufficient flight path response.

Discussion: A STOL airplane with a horizontal complementary control is not much different from a conventional airplane. If a positive thrust component is applied without nose up control to counter the speed increase then flight path angle increases rather slowly, i.e., it is a low bandwidth technique. The buildup in flight path angle can be improved considerably by regulating speed even slightly with the attitude control.

Finding: CTOL technique* is preferred for tight tracking with horizontal controls although analysis shows either technique is usable.

Discussion: For an aircraft having a horizontal control, flight path control with attitude works with just low frequency speed-to-throttle regulation. But flight path-to-throttle requires a more difficult high frequency control of speed with attitude. Hence, a CTOL technique is preferred for tight tracking. However, trimming must still be done with a STOL technique.

Finding: The primary problems in using the nozzle control of this particular design (AWJSRA) were the low control sensitivity and marginal control power (i.e., maximum obtainable change in steady-state flight path).

Discussion: These control features, using nozzle alone, were not apparent in calm air but was apparent in turbulence.

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* CTOL piloting technique refers to use of attitude as the primary flight path control.

Finding: Measures for flight path control characteristics appearing most meaningful in the analysis of results are:

Sensitivity -- Normalized acceleration per unit control movement (e.g., $\partial n_z/\partial \delta_T$)

Control Power -- Maximum up $\Delta\gamma$ and maximum down $\Delta\gamma$ while maintaining approach speed

Bandwidth -- Frequency at which glide slope deviation lags control by 135 deg

Cross-coupling -- Ratio of $\Delta\gamma/\delta_T$ without speed control to $\Delta\gamma/\delta_T$ with perfect speed control (i.e., μ^{STOL}).

Discussion: This classification scheme is an effort to set forth a way of framing flight path control acceptability. The qualities listed here are fundamental to any control situation. Having established these definitions, the next step is to assign numerical limits based on experimental results. Transformation from frequency to time domain may be advantageous, especially for flight test considerations.

Finding: The bare airframe was acceptable in calm air, but in turbulence workload increased greatly with the main problem being lateral flight path control. This indicated that the attitude stability augmentation system normally used in these experiments was more helpful in relieving lateral-directional workload than longitudinal.

Discussion: Poor lateral-directional dynamics appear to be characteristic of STOL aircraft. Problems arise from poor turn coordination and low dihedral effect. The SAS used here was effective in minimizing the effect of these. On the other hand, the bare airframe pitch dynamics did not trouble pilots particularly, even though the short period was overdamped and frequency low (also characteristic of STOL's).

Implication: Some minimum level of lateral-directional stability and control is probably required. However, the problems and the cures are really no different in STOL's than in conventional aircraft.

Finding: Improved performance and pilot opinion was obtained when a flight director was introduced. The area of most improvement was lateral lineup at breakout.

Discussion: A three-axis flight director was provided the pilot to demonstrate the magnitude of flight path control improvement possible. The director gave pitch, roll, and throttle commands. While some improvement was noted in calm air, the major beneficial effect was observed in turbulence. The improvement was in the form of both workload and performance, especially in lateral flight path.

Implication: Use of a flight director could have a mitigating effect on marginal airframe flight path control characteristics especially in more severe atmospheric disturbance conditions.

B. FLARE AND LANDING

Finding: The 65 kt baseline case had acceptable flare and landing characteristics, however disturbance intensity strongly affected pilot opinion and performance.

Discussion: In calm air, the airplane was regarded as satisfactory with pilot ratings all in the vicinity of 3.5. With the winds, shears, and gust levels used in this experiment, the ratings for the 65 kt case worsened to around 6 (i.e., nearly unacceptable). A major problem in turbulence was in initiating flare with a correct power setting. Last minute power corrections for gusts would frequently cause an off-nominal throttle setting which would, in turn, affect the flare and landing characteristics of the airplane. An engine RPM deviation of approximately +1% would result in an aerodynamic configuration prone to floating beyond the touchdown zone. On the other hand, a deviation of -1% created a serious hard landing tendency.

Implication: There may be reason to include effects of off-nominal power settings in any landing performance demonstrations. This would be equivalent to approaches made over a range of aerodynamic flight path angles.

<u>Finding</u>: In general, winds and turbulence had the disturbing effect of making the 10 to 90 percentile range of touchdown points two to three times the length of the touchdown zone. This was true regardless of approach speed.

<u>Discussion</u>: At 65 kt, the near optimum approach speed with respect to landing performance, the 10 to 90 percentile distribution of landings in calm air ranged from 200 ft from the threshold to slightly beyond 500 ft. When turbulence was added the corresponding range became 200 to 800 ft. (The touchdown zone was 300 to 500 ft.)

<u>Implication</u>: These large adverse effects of turbulence and wind on landing precision must be effectively addressed by airworthiness criteria. A direct demonstration approach would be difficult and perhaps impractical. One possible approach is to separate the causes of landing dispersions into:

i. Off-nominal flight path conditions just prior to flare

ii. Disturbance of flight path from gusts during flare.

A calm air landing demonstration at say an off-nominal power setting would address the first item. Provision for an adequate level of flight path controllability would insure against the second.

<u>Finding</u>: Decreasing the approach speed resulted in worsening pilot opinion to an unacceptable level at slightly less than 65 kt, about the same point at which ILS tracking became unacceptable.

<u>Discussion</u>: As with glide slope tracking, pilot opinion of the flare and landing steadily worsened as the approach speed was decreased. This was true for the BR 941S simulation as well. Also, the fact that the minimum acceptable approach speed for flare and landing matched that for ILS tracking may not be a coincidence. Rather, it is hypothesized that the pilot gauges his flight path control performance on his ability to achieve a flare window precision which will result in acceptable flare and landing performance. To the extent that this is true, it is important to judge an ILS tracking task in conjunction with a flare and landing task.

<u>Finding</u>: As with ILS tracking, an increase in approach speed had little effect on flare and landing ratings; however, landing performance suffered.

Discussion: Higher approach speeds were characterized by a strong tendency to land long, especially in the presence of turbulence and winds. There was also a tendency to land hard at the higher approach speeds. The reason for no corresponding change in pilot ratings is not clear.

Implication: The worsening of landing performance, especially the tendency to land long, gives reason to consider an upper limit on approach speed.

Finding: Tailwinds were found roughly equivalent to decreasing approach speed with the pilot having to modify the flare to maintain touchdown sink rate performance. An increase in approach speed was required to offset losses in margin from V_{min} or α_{max}.

Discussion: In general, winds had an effect roughly equivalent to a change in approach speed with tailwinds having a large adverse effect. A tailwind required a lower power setting (but a higher sink rate) which reduced the margin above V_{min} or below α_{max}. The effect was roughly equivalent to an approach speed change of 1/2 the wind speed, i.e., to compensate for a 10 kt tailwind, increase approach speed 5 kt. Thus conceivably, a 10 kt tailwind could result in a 15 kt increase in ground speed and a 50% increase in stopping distance (assuming stopping distance is proportional to ground speed squared).

Implication: Winds should be taken into account when defining allowable landing conditions and when setting landing field length requirements.

Finding: Subsequent analysis has shown that glide path/touchdown zone geometry can have a significant influence on landing performance obtainable for a given airframe/flight condition combination. These factors were apparently favorable for the baseline case. They were not favorable for significantly higher and lower speeds, thus perhaps they contributed to landing problems.

Discussion: Landing performance and pilot workload are affected by the relative locations of the glide slope/runway intercept and the touchdown zone. The effects are a function of airplane dynamics, glide path angle, size of touchdown zone, range of allowable touchdown sink rates, and surface winds. The 65 kt approach case appeared to be compatible with the airport

geometry used for this simulation. The pilot opinion of other approach speed cases may have suffered to some extent because the touchdown zone was either too far or too close to the glide path/runway intercept.

Implication: Landing criteria require consideration of landing geometry. Once a standard STOL runway is set then all aircraft will have to operate with that fixed geometry. Unfortunately, what may be the optimum geometry for one STOL design may not be appropriate for another.

Finding: . Using power to flare may, for some STOL aircraft, be preferable to using pitch attitude. The acceptability of power to flare depends on the altitude bandwidth which can be achieved.

Discussion: One pilot evaluated the use of DLC on the AWJSRA simulation. He preferred to use DLC to flare and rated that technique very highly. The primary difference between DLC and the normal throttle control was response lag. DLC was instantaneous while the throttle had a 0.7 sec engine lag. A similar result was obtained in the BR 941S simulation; flare with power alone was acceptable if the engine lags were small enough. In an actual airplane, the required response could be obtained using a washed-out crossfeed from the throttle to a DLC.

Engine lags, per se, are not important to the pilot. He is concerned with the lags between his control inputs and aircraft response. Consequently, an airworthiness criterion for flare with power only (or with attitude) should include some measure of aircraft response lags, such as the altitude control bandwidth which can be achieved.

Implication: Consideration should be given to allowing flares with power alone and a suitable criterion should be formulated. A single criterion which covers flaring with either power or attitude is a definite possibility.

Finding: A linear closed-loop feedback control model was developed to analyze the flare, in particular the relationship between the flare maneuver and the resulting touchdown performance.

Discussion: This model was important in showing that the flare and landing was essentially a closed-loop flight path control situation not

unlike glide slope tracking. The fundamental differences are the importance of terminal conditions (sink rate and distance along the runway) and the fact that the control technique may switch from, say, a two-control STOL technique on the glide slope ($u \longrightarrow \theta$, $\gamma \longrightarrow \delta_T$) to a one-control CTOL technique ($h \longrightarrow \dot{\theta}$) during flare.

Implication: This suggests that the same basic flight path criteria used for the approach task might be modified to fit the flare and landing task, too.

Finding: The most useful vehicle for describing flare and landing characteristics of a given configuration was a plot of touchdown performance contours as functions of flare attitude and flare height. With such a mapping the sensitivity of touchdown performance to the flare parameters was shown, as well as the compatibility of the touchdown zone geometry with the airframe.

Discussion: A model of the calm-air, attitude-only flare maneuver was formulated. This model was used to compute touchdown conditions as a function of the two parameters which describe the flare maneuver - flare height and pitch change during the flare.

Implication: Landing criteria should consider the sensitivity of touchdown conditions to pilot flare parameters. Certainly if a "successful" landing requires a precision of flare height or flare attitude beyond the capability of the pilot, the situation is unacceptable. A sensitivity criterion might be stated in terms of allowable dispersions in touchdown conditions measured over a series of landings.

Finding: Variations in approach speeds, winds, and ground effect resulted in pilots making adjustments in their flare maneuver appropriate to optimizing landing performance. This lends additional credence to the use of this simulator in flare and landing studies.

Discussion: Over an appropriate learning period, pilots were observed to make adjustments in their flare maneuver according to what one would predict from the flare model discussed above. This seems to imply an adequate level of visual or other cues required for flare and landing in the simulator.

C. GO-AROUND

<u>Finding</u>: AEO go-arounds presented no problems in terms of either pilot workload or performance.

<u>Discussion</u>: With all engines operating, go-arounds were easy for the pilot to perform in spite of the reconfiguration tasks required (i.e., nozzles to horizontal and flaps to 30 deg).

<u>Implication</u>: Normal go-arounds in STOL aircraft can probably be considered no different than for conventional aircraft except for the need to reconfigure.

<u>Finding</u>: OEI go-arounds, on the other hand, did require considerable pilot skill as well as aid from the right seat occupant.

<u>Discussion</u>: The AWJSRA simulation presented the pilot with four major areas of difficulty not present with the BR 941S. They were:

- A larger proportion of thrust loss
- Confusing cues as to which engine had failed
- More separate control manipulations required
- Asymmetric transients due to configuration changes (i.e., asymmetric nozzle)

The greater power loss following an engine failure on the AWJSRA was credited to the fact that it was a twin engine aircraft while the BR 941S was a four engine aircraft. This problem would not be as severe in a four engine augmentor wing given equal AEO performance.

In a conventional multi-engine aircraft, an engine failure tends to produce roll and yaw motions in the same sense, i.e., failure of a left engine results in a left yaw and a left roll. On the AWJSRA, failure of the left engine results in a left yaw but a right roll. The pilots found these engine-out cues to be confusing and resulted in longer delays prior to corrective action. This problem could be reduced by pilot training or by design considerations. The BR 941S, of course, presented no lateral-directional cues at all due to the propeller cross-shafting.

Once the pilot recognized an engine failure, he had to manipulate four distinct controls to initiate a go-around, i.e., nozzles, throttles, flaps had to be set at their go-around positions, and the aircraft had to be pitched to a 12 - 14 deg attitude. By contrast, the BR 941S was configured such that the go-around configuration was easier to obtain.

Additionally, the nozzles not only had to be changed from an approach to a go-around setting, they had to be changed at the proper rate. Too small of a nozzle rate would result in an unacceptably large altitude loss and roll attitude, while too large a nozzle rate resulted in full throw rudder inputs to counteract the yawing moments from the nozzles.

Finding: Altitude losses with OEI were approximately 115 ft with a standard deviation of about 20 ft.

Discussion: The OEI performance observed in the BR 941S and AWJSRA simulations probably bracket the range of STOL aircraft. For the BR 941S, mean OEI altitude losses were 40 to 60 ft depending on the use of transparency. The AWJSRA exhibited losses in excess of 100 ft even though the steady-state angle of climb was the same (about +4 deg). The prime determining factor in altitude loss for a given steady-state climb is the effective flight path response. This is determined by:

- Engine response time (maximum power acceleration)
- Basic airframe flight path response (bandwidth)
- Reconfiguration time.

For the two subject STOL's these respective response times would be approximately:

	BR 941S	AWJSRA
Engine	1.5 sec	0.7 sec
Airframe	1.5 sec	2.0 sec
Reconfiguration	2.3 sec	5.5 sec

The altitude loss for each was about proportional to the response time of the limiting factor. In both cases, this limiting factor is reconfiguration

time. The engine and airframe contributions for each aircraft are representative of STOL's and effectively set a limit on minimum altitude loss. This limit would probably be on the order of the BR 941S response.

Implication: To the extent that long flight path response times are present in STOL aircraft, then a large altitude loss is possible during a go-around. It seems reasonable to consider some limit on altitude loss relative to descent minimums.

D. TAKEOFF

Finding: This airplane was sensitive to the choice of V_1 in terms of distance to 35 ft altitude because of the twin engine design (i.e., a large thrust decrement with loss of power).

Discussion: This observation is based on the variation of distance to 35 ft with the speed at which the engine is cut. For the BR 941S, a four engine airplane, the variation in this distance was only about 200 ft over the entire range of engine cut speeds. For the AWJSRA, a twin engine design, distance to 35 ft varied from 3000 ft with an engine cut at 30 kt to 1600 ft (the balanced field length) with an engine cut at 60 kt.

Implication: Any requirement for a margin between V_1 and V_R would significantly increase the takeoff field length of this aircraft.

Finding: A lower limit on V_1 was set by a V_{MCG} of about 30 kt.

Discussion: The prolonged lateral asymmetry following early engine cuts resulted in an uncontrollable drift off the runway before becoming airborne. This effect did not show up in BR 941S tests due to its lack of OEI asymmetry.

Finding: Neither crosswinds nor turbulence had a significant effect on takeoff performance.

Discussion: Pilots experienced no particular difficulties in coping with winds and turbulence for either the BR 941S or AWJSRA simulations.

Implication: While winds and turbulence should be included in approach and landing criteria, no special consideration is required for takeoff other than the effects on performance.

Finding: The airplane was forgiving of abuses of V_R and V_2.

Discussion: Both the BR 941S and AWJSRA simulations had a tolerance for large abuses of V_R and V_2 at least in terms of handling qualities. The limit was only when a V_2 abuse was so large that V_{min} was approached. In the actual AWJSRA, a V_R abuse in a crosswind presents some problems due to the available lateral-directional control power.

Implication: Requirements to demonstrate V_R and V_2 abuses may only be necessary to demonstrate performance penalties, not handling quality problems.

SECTION III

AIRWORTHINESS CRITERIA

This section discusses potential airworthiness criteria for STOL aircraft in light of the results from the BR 941S and AWJSRA simulation experiments to date. This discussion includes a considered opinion of how well present conventional aircraft airworthiness criteria apply in the areas studied, and to what extent special STOL criteria are needed. The factors which should be given attention in arriving at new airworthiness criteria are mentioned in at least general terms; and, where possible, specific criteria are offered for consideration.

This section is organized parallel to the previous one. The first two parts, ILS tracking and flare and landing, receive the most attention since these are areas where STOL's differ most from conventional aircraft. Go-around and takeoff aspects are comparatively uncomplicated.

A. ILS TRACKING

The central airworthiness issue involved in the ILS tracking task is the guarantee of an <u>acceptable level of longitudinal flight path control</u> while allowing for a number of potential adversities. This characteristic is essentially guaranteed for conventional aircraft by the 1.3 V_s minimum approach speed requirement of FAR Part 25. The reason for this guarantee is the limited range of airplane dynamics implied by a margin above stall, combined with normally expected ranges of wing aspect ratio, wing loading, and maximum obtainable lift coefficients of unblown or mildly blown* wings. The use of a stall margin limit for conventional airplanes is indeed an effective device.

Unfortunately, the use of significant levels of powered lift upsets the conventional relationship between flight path dynamics and stall margin. The results to date from this study indicate no effective guarantee of adequate longitudinal flight path control by specifying an approach speed

* Such mild blowing would include immersion of a portion of the flap span in a propeller slipstream as well as the use of BLC.

relative to stall or minimum speed. This is not to say that some easily expressible relationship may not be found. However, in lieu of such a fortuitous find, it seems reasonable at this point to approach the question of flight path control directly. We propose to do this by defining it in terms common to virtually any control situation. Then it is possible to quantify directly those defining factors and thereby assure the needed level of control.

As a starting point, the suggested method of quantifying the level of flight path control is to break flight path control into the elements of:

- Control sensitivity
- Control power
- Control bandwidth
- Control cross-coupling.

Next, we would strive to quantify the limits of each while trying to allow for possible tradeoffs of one element for another. Finally, armed with what qualitatively assures an adequate level of flight path control one could then identify an envelope of acceptable operating conditions (or lack of such) given a set of adversity factors such as likely atmospheric conditions and potential operating point abuses. This, then, is the approach stated in general terms. The following paragraphs will develop this with the aim of establishing some specific ideas for airworthiness criteria.

For our purposes, the above flight path control elements can be briefly defined as follows:

<u>Control Sensitivity</u>: The ratio of short-term response to a unit control input (really, a large enough input to be representative of normal flight path corrections).

<u>Control Power</u>: Available range of flight path angle or rate of descent excursions, both short-term and long-term.

<u>Control Bandwidth</u>: Quickness with which flight path corrections can be made.

<u>Control Cross-Coupling</u>: Degree of difficulty in controlling airspeed and flight path angle simultaneously, both short-term and long-term.

It should be noted that the elements of flight path control presented here are not new. Each has been the direct or indirect subject of a number of studies. Flight path control sensitivity for vertical thrust orientation has been investigated in conjunction with helicopter collective control. The FAA-sponsored study of Reference 3 included a brief variation of control sensitivity specifically for a STOL vehicle. Flight path control power is a part of several suggested criteria including those of References 4, 5, and 6. Bandwidth has been the subject of numerous studies involving all types of aircraft. Proposals to use some measure of bandwidth in FAA airworthiness standards are included in References 4, 5, and 6. FAR Part XX offers a qualitative criteria to restrict objectionable cross-coupling in very general terms. Control cross-coupling of STOL airplanes was studied directly in the work of Reference 3. Since then quantification of the cross-coupling problem has been increasingly recognized as a major concern.

Quantitatively defining each of these elements for the ultimate purpose of incorporation into airworthiness standards requires careful attention. Limits should be set within the context of reasonable piloting technique yet they should be mainly a measure of airframe qualities and not the pilot. Also, flight test measurement and design computation of criteria should be easily accomplished. The ideas offered in the following pages do not completely satisfy these requirements but do form a basis for further refinement.

In order to establish some quantitative measure of the flight path control elements we shall initially depend on the definitions developed in Volume Two. These definitions are outlined in Table III-1. The advantages of these particular measures of the control characteristics are that they are easily computed and they effectively bracket the degrees of airspeed control from none at all to perfect airspeed regulation. Practically speaking, maintaining any particular flight reference (e.g., angle of attack) would fall within this speed control spectrum.

To illustrate the numerical values involved in the breakdown of flight path control used here, let's consider a collection of STOL configurations from both the BR 941S and AWJSRA simulations. Each of these represent a marginal configuration, i.e., a pilot opinion rating of 6.5 was given in equally "severe" atmospheric conditions (each case was chosen by means of

TABLE III-1

QUANTITATIVE DEFINITIONS OF FLIGHT PATH CONTROL CHARACTERISTICS

CHARACTERISTIC	DEFINITION	LIMITS
Control Sensitivity $\frac{\partial n}{\partial \delta}$	Normalized acceleration per unit control deflection (in the direction of the effective thrust vector)	We would expect upper and lower sensitivity limits. Numerical values of these limits have been the subject of several studies.
Control Power $\Delta\gamma_{max}$, $\Delta\gamma_{min}$	Available excursion of flight path angle up and down at a constant speed within a specified short-term and and steady-state	Traditionally the capability to make a down correction has been more of a concern than an up correction. A 2 deg down correction capability has been suggested by some. We would expect to see a well defined limit on both up and down capability.
Control Bandwidth ω_{BW_θ}, ω_{BW_u}	Frequency at which the flight path response output lags the control input by 135 deg for: a. Attitude held constant b. Airspeed held constant	A lower limit would be expected. The numerical value would depend on how quickly the pilot desires to make flight path corrections for a given task. A constant θ or constant u constraint would be more applicable depending on how tightly the pilot holds airspeed or another flight reference.
Control Cross-Coupling μ_0^{STOL}, $\mu_{.3}^{STOL}$	The ratio of the γ/δ transfer function with no airspeed regulation to the value with perfect speed regulation evaluated at: a. Steady-state ($\omega = 0$) b. Tight glide slope tracking frequency ($\omega = .3$ rad/sec)	Ideally μ^{STOL} would be unity at all frequencies. We would expect to see a limit on how far μ_0^{STOL} and $\mu_{.3}^{STOL}$ could vary from unity. Also, since $\mu^{STOL} > 1$ and $\mu^{STOL} < 1$ reflect fundamentally different coupling characteristics we would expect to see a limit on how much μ_0^{STOL} could differ from $\mu_{.3}^{STOL}$.

a cross plot of pilot rating versus approach speed). The cases consist of:

BR 941S $\delta_f = 95$, $T^* = 12$, $V = 59$ kt

BR 941S $\delta_f = 95$, $T = 0$, $V = 63$ kt

AWJSRA $\delta_f = 65$, $\delta_\nu = 75$, $\tau_E = .7$ sec, $V = 63$ kt

AWJSRA $\delta_f = 65$, $\delta_\nu = 75$, $\tau_E = 1.5$ sec, $V = 65$ kt

Levels of longitudinal and lateral-directional attitude control are essentially equal for each of the above.

Table III-2 shows a table of flight path control parameters in terms of the above criteria for the cases at the approach speed for marginal ratings.

TABLE III-2

FLIGHT PATH CONTROL - MARGINAL CONDITIONS (POR $\doteq$ 6.5)

	Sensitivity	Control Power (Steady State)		Bandwidth		Cross-Coupling	
	$\frac{\partial n}{\partial \delta_T}$	$\Delta\gamma_{max}$	$\Delta\gamma_{min}$	ω_{BW_θ}	ω_{BW_u}	μ_0^{STOL}	$\mu_{.3}^{STOL}$
	g/in	deg	deg	rad/sec	rad/sec	——	——
BR 941 S							
$T = 12$, $V = 59$ kt	.10	+7	-6	.23	.24	.95	1.15
$T = 0$, $V = 63$ kt	.06	12.7	-3.6	.25	.29	.95	1.2
AWJSRA							
$\tau_E = .7$ sec	.16	11.8	-6	.34	.35	.80	1.7
$\tau_E = 1.5$ sec	.16	11.7	-6.3	.28	.26	.86	1.7

One disappointing feature of this table is the apparent inconsistency of the characteristics, especially in cross-coupling. However, what we may fail to

*Transparency as used in the BR 941S was a differential inboard and outboard propeller pitch.

take into account by looking only at nominal (on speed) conditions is the possible sensitivity to abuses. Since we would expect degradation with a low speed abuse let's tabulate the same criteria assuming a -5 kt abuse. This is shown in Table III-3.

TABLE III-3

FLIGHT PATH CONTROL - MARGINAL CONDITIONS MINUS 5 KT

	Sensitivity	Control Power (Steady State)		Bandwidth		Cross-Coupling	
	$\frac{\partial n}{\partial \delta_T}$	$\Delta\gamma_{max}$	$\Delta\gamma_{min}$	ω_{BW_θ}	ω_{BW_u}	μ_0^{STOL}	$\mu_{.3}^{STOL}$
	g/in	deg	deg	rad/sec	rad/sec	——	——
BR 941S							
T = 12, V = 54 kt	.09	6.6	-1.	.25	.18	.7	1.5
T = 0, V = 58 kt	.07	11	-2.7	.28	.22	.75	1.5
AWJSRA							
τ_E = .7 sec	.15	11.6	-5.5	.35	.34	.6	1.7
τ_E = 1.5 sec	.16	11.9	-5.8	.28	.26	.6	1.7

Table III-3 shows that the BR 941S was, in fact, sensitive to off-nominal abuse in terms of high frequency cross-coupling and steady-state down correction capability. Having included the effect of a speed abuse we see a fairly consistent set of numerical values especially in the cross-coupling criteria.

Based mainly on the above, the following flight path control characteristics represent a reasonable estimate of what is required for adequate flight path control.

Control Sensitivity: .02 to .08 g/cm (.05 to .2 g/in) for a lever control. (If pitch attitude is used as a primary flight path control then a minimum of around 1 g/rad is probably required based on MIL-F-8785B.)

Control Power: $\pm$ 4 deg long term. Based on BR 941S results, less is required for an abuse condition, say $\pm$ 2 deg. For short term, using the bandwidth limit given below, $\pm$ 2 deg in 3 sec. These, however, are based on sketchy data and will be the subject of further investigation.

Control Bandwidth: .25 rad/sec is a reasonably well defined value based mainly on engine lag variations.

Control Cross-Coupling: For μ^{STOL} increasing with ω, the low frequency value, μ_0^{STOL}, should be greater than .8 and the high frequency value, $\mu_{.3}^{STOL}$, less than 1.7. For μ^{STOL} decreasing with ω the low frequency value should be less than 1.1 and the high frequency greater than .3. For abuse conditions the low frequency values can probably be somewhat relaxed. These rules are really just an educated guess based on theoretical interpretation of μ^{STOL} and relatively few numerical examples. This also will be the subject of further investigation.

The above flight path control characteristics apply to the airspeed and flight path angle operating region. Thus, in this operating region a certain level of control adequacy exists. However, this operating region should still be reasonably well separated from any point at which there is a massive degradation of flight path control, e.g. stall. Therefore, an angle of attack and airspeed margin is considered appropriate.

Now, let's try to fit the preceding ideas into a format resembling airworthiness criteria for the ILS approach phase. In doing so we will by and large use the flight path control parameters defined above except we will attempt to handle control technique in a more suitable manner, i.e., the idealized concept of perfect airspeed control will be relaxed.

The criteria will be arranged in the following organizational scheme:

- Allowable STOL approach conditions
- Flight path control characteristics
- Flight path control margins.

The allowable approach conditions are no more than trim conditions and thus could be described by a γ - V plot as in Figure III-1. The factors which describe trim conditions are:

- Aerodynamic configuration (flaps, etc.)
- Loading configuration (weight, c.g.)
- Target flight reference (airspeed, angle of attack, etc.)
- Glide slope angle
- Mean wind conditions
- Failure states (engine out, SAS failed, etc.).

For the allowable approach conditions and for reasonable abuses, the flight path control characteristics must be acceptable. Furthermore, these characteristics must be evaluated for a realistic control input. One possible scheme for handling control inputs is to allow only use of the primary flight path control when evaluating sensitivity, control power, and bandwidth. (Cross-coupling involves both the primary and secondary control.) For example if the primary control were attitude (CTOL technique) then bandwidth would be evaluated by evaluating the phase lag between glide slope error and the attitude control for sinusoidal inputs without any use of throttle. However, such a scheme may be overly restrictive in some cases. As an example, evaluation of long term control power using attitude control only would not give a favorable result except for extreme frontside operation. With leisurely use of the secondary control (i.e., throttle) the control power situation could improve considerably. Thus, some allowance for use of secondary control appears reasonable.

At the other extreme, too active a use of secondary control is unrealistic. For example, the perfect airspeed regulation assumptions used previously might require unduly high piloting skill and workload to accomplish. Therefore a compromise is suggested for the involvement of a secondary control.

A possible scheme for evaluation of flight path control characteristics which permits reasonable use of secondary control is to allow secondary control inputs proportional to primary control inputs. The level of proportionality would be that necessary to maintain a prescribed flight reference

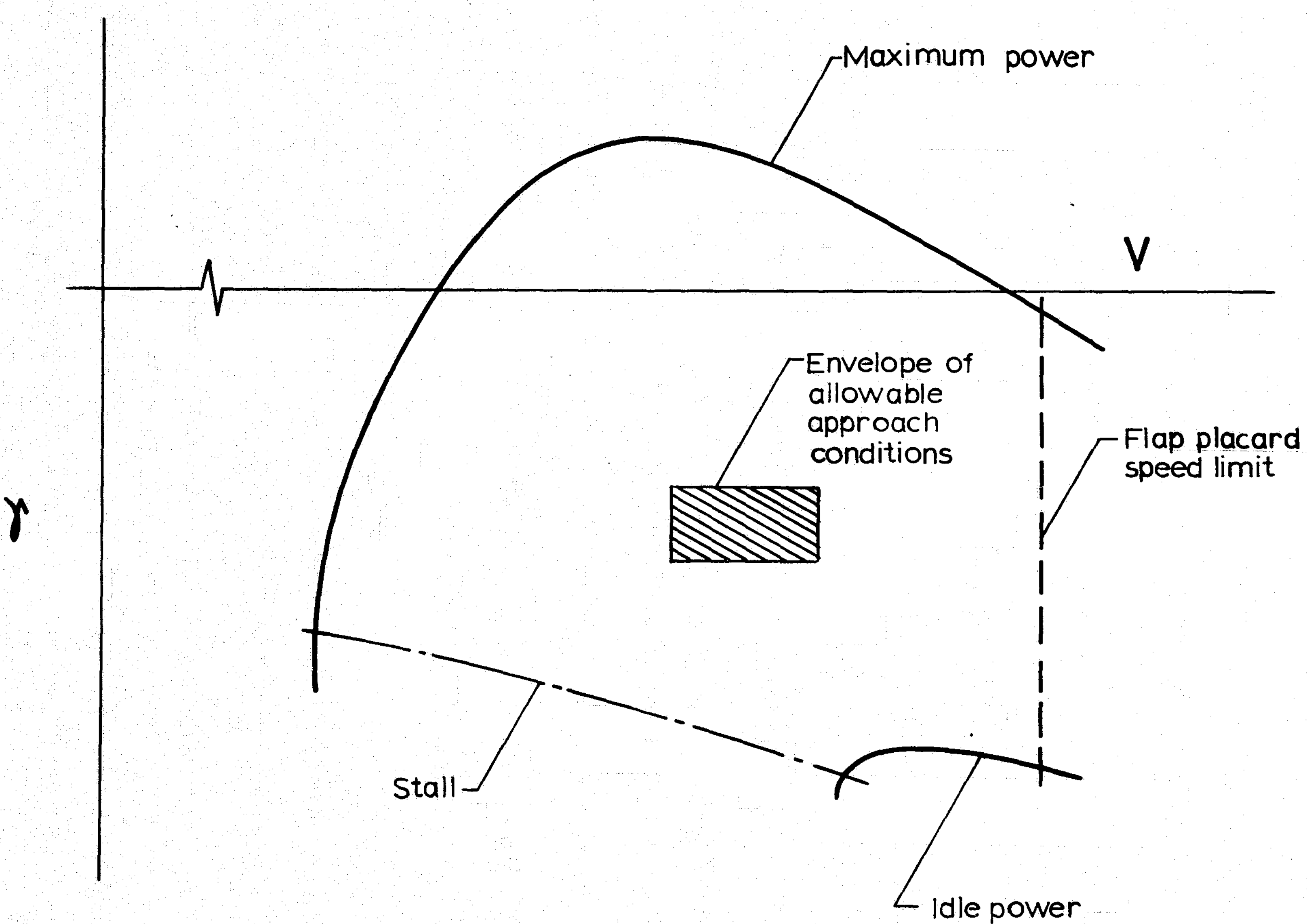

Figure III-1

Example of Allowable Approach Conditions

such as airspeed, angle of attack, attitude, or a derived reference as given by a flight director. This use of secondary control relative to primary control is considered reasonable while not allowing the element of piloting skill to enter the evaluation of airframe flight path control characteristics.

As discussed earlier, there is reason to believe that some level of flight path control should exist for an abuse of the allowable approach conditions, in particular, airspeed. Based on the observations of approaches with the BR 941S and AWJSRA simulations, an airspeed abuse of about 5 kt seems reasonable to consider initially. Note that specification of abuse in terms of airspeed per se is somewhat arbitrary. Certainly it could be expressed in terms of a number of quantities such as angle of attack or attitude.

The degree of allowable flight path control degradation for abuse conditions has not been well defined. Therefore, for the present we will rely on the levels present for the cases tabulated previously. These suggest a relaxation in long term control power and long term cross-coupling, both a natural consequence of a low speed abuse.

To help summarize the suggested application of flight path control criteria for the allowable approach conditions and for abuse conditions, a γ - V plot is shown in Figure III-2, which is a further advanced version of Figure III-1.

The last feature of the STOL approach flight path control criteria to be set forth here is the specification of margins relative to massive degradation of flight path control. These margins would provide a kind of outer shell of protection around the allowable approach conditions and the surrounding flight path control power and airspeed abuse regions.

The margins considered relevant here involve both angle of attack and airspeed. However, since there may be a significant power effect on lift, the margins need to be tied to a given power setting. One meaningful evaluation of margins for a given approach condition is to measure the margin relative to the respective approach power setting. At the same time some reduced but still positive margin is required for a reasonable power reduction. The scheme suggested here would be to apply a set of margin limits to the nominal approach condition and a second set to the power change required to fulfill the flight path control power requirement. The margins themselves would consist of:

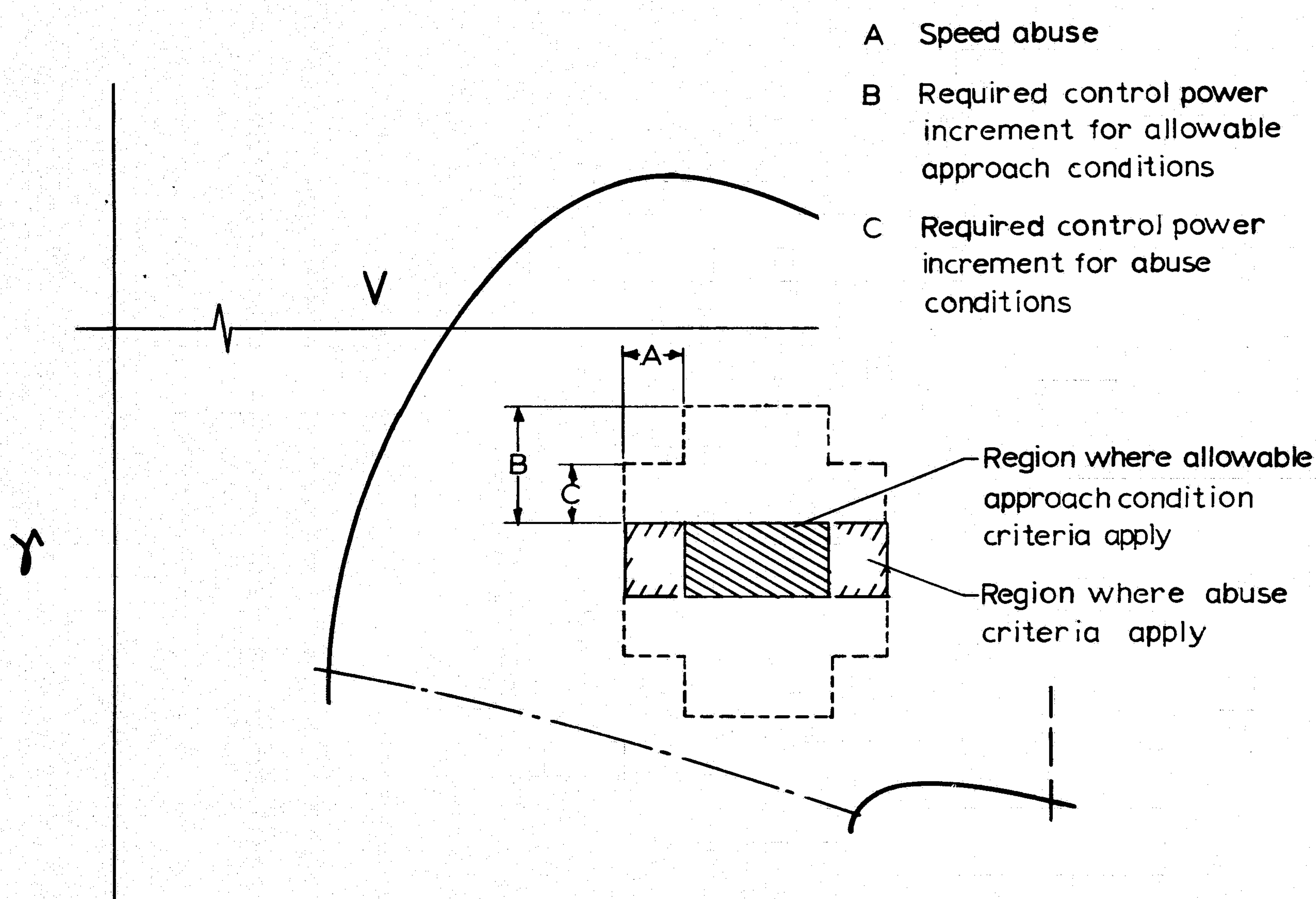

Figure III-2

Example of Flight Path Control Criteria Application

- A speed margin above minimum speed
- An angle of attack margin below loss of control, abrupt stall, and maximum demonstrated angle of attack.

The application of these is illustrated in Figure III-3. Numerical description of these limits is not possible at this point, but should be the subject of future work.

The above suggestions for airworthiness criteria relative to the approach phase are summarized in Table III-4. This specific formulation of STOL approach flight control criteria, of course, requires refinement, especially numerically. However, its strong point is considered to be the requirement for an "envelope" of STOL approach conditions, then, given this envelope, the application of criteria which directly govern flight path control characteristics, both dynamic and steady-state.

The main weakness in this formulation of approach flight path control criteria is the way in which bandwidth and control cross-coupling are quantified. While they lend themselves to straightforward computation from known aerodynamics and propulsion data, they are not necessarily well suited to direct measurement in flight. However, this is not considered a serious problem since similar measures of bandwidth and cross-coupling could be developed based on, say, time responses to step inputs. Once the basic validity of this approach has been established, additional work can be devoted to relating these criteria to more easily measured ones.

Another problem with the criteria presented here involves the specific numerical values. In most cases the values shown are considered representative of final values. Better definition should be the subject of future tests.

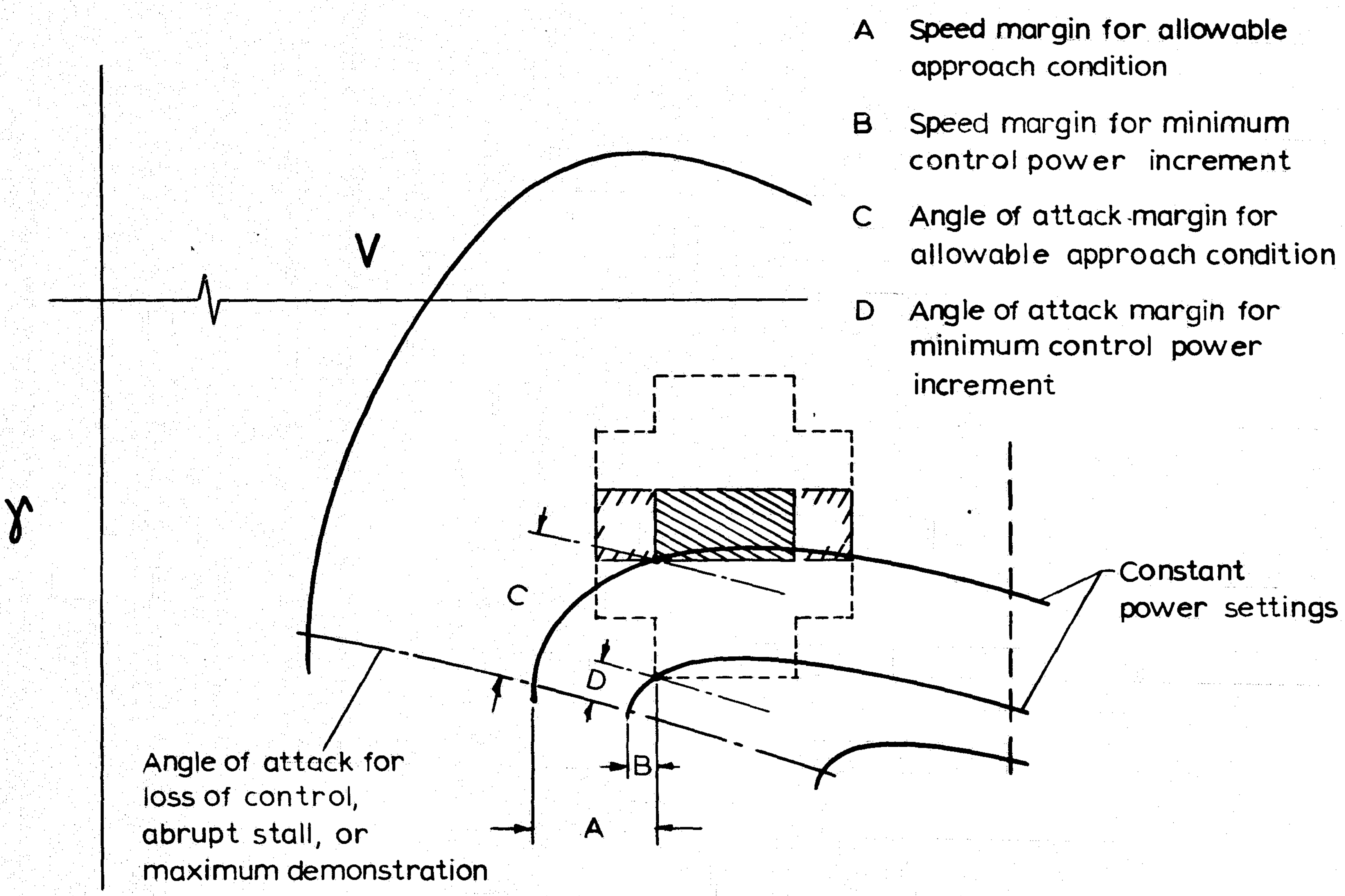

Figure III-3

Example of Airspeed and Angle of Attack Margins

TABLE III-4

APPROACH CRITERIA SUMMARY

--- Allowable STOL Approach Conditions

The conditions under which STOL approaches may be flown must be specified in terms of allowable ranges of:

(a) Aerodynamic configuration

(b) Loading configuration

(c) Target airspeed (or AOA)

(d) Glide slope angle

(e) Surface wind conditions

(f) Failure states (with probability level > ?)

--- Longitudinal Flight Path Control Characteristics - STOL Approach

The longitudinal flight path control characteristics for operation over all combinations of allowable STOL approach conditions must meet the criteria of Column 1, Table A; and for abuses of up to ± 5 kt from target conditions, the criteria of Column 2, Table A. The control permitted to meet these conditions is limited to a single primary flight path control plus proportional use of a secondary control. The proportion of secondary control may range from zero to that required for a constant flight path reference in the long term.

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TABLE A

	COLUMN 1	COLUMN 2
CONTROL CHARACTERISTIC	CRITERIA WITHIN ALLOWABLE STOL APPROACH CONDITIONS	CRITERIA FOR AIRSPEED ABUSES UP TO ± 5 KT FROM THE ALLOWABLE STOL APPROACH CONDITIONS
FLIGHT PATH CONTROL SENSITIVITY	Normalized acceleration resultant per unit control input up or down within: (1) $.02 \frac{g}{cm}$ ($.05 \frac{g}{in}$) to $.08 \frac{g}{cm}$ ($.2 \frac{g}{in}$) for cockpit lever control (2) $1 \frac{g}{rad}$ to ? for pitch attitude control	Same as Column 1
FLIGHT PATH CONTROL POWER	Capability for: (1) Sustained correction of 4 deg (?) up and down (2) Short-term correction of 2 deg (?) up and down in 3 sec (?).	Capability for sustained correction of 2 deg (?) up or down.
FLIGHT PATH CONTROL BANDWIDTH	Glide slope error corrections must not lag control inputs by more than 135 deg at .25 rad/sec (?).	Same as Column 1
FLIGHT PATH CONTROL CROSS-COUPLING	Cross-coupling of airspeed and glide slope corrections as measured by the function μ^{STOL} must remain within the following limits: (1) For μ^{STOL} generally increasing $\omega = 0$ to $\omega = .3$ rad/sec $\mu_0^{STOL} > .8$ $\mu_{.3}^{STOL} < 1.7$ (2) For μ^{STOL} generally decreasing from $\omega = 0$ to $\omega = .3$ rad/sec $\mu_0^{STOL} < 1.1$ $\mu_{.3}^{STOL} > .3$	Same as Column 1 except for long-term corrections: $.6 \le \mu_0^{STOL} \le 1.2$ (?)

TABLE III-4 (Concluded)

 # --- Longitudinal Flight Path Control Margins - STOL Approach

The speed and angle of attack margins for the allowable STOL approach conditions shall be at least those given in Column 1, Table B; and for flight path angles of up to ± 4 deg from the allowable approach conditions, those of Column 2, Table B.

TABLE B

	COLUMN 1	COLUMN 2
MARGINS (At Approach Power)		
Speed margin above minimum speed	?	?
Angle of attack margin below loss of control, abrupt stall, and maximum demonstrated angle of attack	?	?

B. FLARE AND LANDING

Where the central issue in the ILS tracking task was the guarantee of an adequate level of flight path control, in the flare and landing task it is the guarantee of an acceptable level of landing precision. Also, similar to flight path control, this acceptable level of precision must allow for a number of potential adversity factors.

For conventional aircraft the emphasis on landing precision is generally directed at touchdown sink rate. The use of 1.3 V_s as a minimum approach speed has served as an effective guarantee for landing precision just as for adequate flight path control. However, this ceases to be an effective governing factor for STOL landing precision for the same reason 1.3 V_s fails to control STOL flight path control characteristics. Also, the STOL problem is further complicated by a requirement for precision in touchdown point along the runway as well as sink rate. Thus, a direct approach was taken toward developing possible flare and landing criteria.

The flare maneuver was found to be basically a closed-loop flight path control problem just as the approach task. Therefore, similar flight path criteria should apply. Flare and landing differs from the approach only to the extent that an end point is involved. Thus steady-state flight path control characteristics are not important. While flight path control power during the approach includes both a short-term and a sustained $\Delta\gamma$ requirement, only a short-term $\Delta\gamma$ requirement is needed in the flare. Margins above severe loss of control during approach were defined for steady-state conditions. In the flare, margins are applicable only in a transient way.

We propose to use the flight path control criteria in a supportive role to a basic demonstration criterion. This basic demonstration is designed to guarantee some minimum acceptable level of landing precision in relatively easily controlled atmospheric conditions, i.e., no specified level of turbulence. The object is to show that landings can be consistently made within some specified sink rate/touchdown point envelope. This, when combined with the flight path control criteria, then provides a certain level of landing precision over a wide range of adversity factors such as atmospheric turbulence. The considerations in modifying the control criteria for flare are presented in Table III-5.

TABLE III-5

FLIGHT PATH CONTROL CRITERIA MODIFIED FOR FLARE

CONTROL CHARACTERISTIC	INTERPRETATION FOR FLARE
Flight Path Control Sensitivity	Allow for primary flare control different from primary flight path control in approach.
Flight Path Control Power	Steady-state flight path angle increment does not really apply since flare and landing is only a short-term maneuver. However, a nominal incremental sink rate sustained for a reasonable duration might be a desirable requirement to reflect a transient sort of control power. This should be demonstrated in ground effect using normal control technique.
Flight Path Control Bandwidth	As with control power, bandwidth would need be only a short-term requirement, but must reflect the flare control used. For attitude-to-flare this would be an $\frac{h}{\theta_c}$ bandwidth ignoring the low frequency inadequacies. For power-to-flare, bandwidth would be measured just as for approach although requirements might be higher for flare.
Flight Path Control Cross-Coupling	Based on observation, use of a second control during flare is of an open loop nature. Thus, a control cross-coupling criteria is probably unnecessary.

The suggestions for airworthiness criteria for the flare and landing phase are summarized in Table III-6. As with the approach criteria, the emphasis has been placed on establishing the general form of the criteria. Numerical values are even less well defined for flare and landing than for the approach.

One particularly difficult problem in designing criteria for flare and landing is in prescribing use of reasonable control technique in a demonstration. While some progress has been made during this program in analyzing the pilot's control structure during flare, it is not yet possible to satisfactorily relate purely airframe flight path control characteristics to a level of landing precision through use of a "standard" technique. Hence, we must rely on the phrase "without exceptional piloting skill".

TABLE III-6

LANDING CRITERIA SUMMARY

• --- STOL Landing Precision Capability

It must be demonstrated that without exceptional piloting skill it is possible to make consistent landings within the following constraints:

- Touchdown sink rate less than ___% of the structural limit; and
- Touchdown point dispersions less than ___% of the minimum certified field length.

This demonstration must be conducted over the allowable ranges of:

- Aerodynamic configuration
- Loading configuration
- Target airspeed ± 5 kt (or a comparable range for other flight references)
- Glide slope angle ± 2 deg
- Surface wind conditions
- Failures.

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• --- Longitudinal Flight Path Control Characteristics - STOL Landing

The longitudinal flight path control characteristics during flare and landing for all combinations of allowable approach conditions must meet the criteria of Table C for a single flare control.

TABLE C

CONTROL CHARACTERISTIC	CRITERIA
Flight Path Control Sensitivity	Normalized acceleration resultant per unit control movement within: • .02 $\frac{g}{cm}$ to .08 $\frac{g}{cm}$ (.05 $\frac{g}{in}$ to .2 $\frac{g}{in}$) (?) for a mechanical controller • 1 $\frac{g}{rad}$ to ___ (?) for a pitch attitude control
Flight Path Control Power	Capability for attaining the lesser of: (a) 50% maximum allowable touchdown sink rate (b) 50% maximum allowable trimmed approach sink rate
Flight Path Control Bandwidth	Altitude error corrections must not lag control inputs by more than 135 deg at .5 rad/sec (?)

• --- Longitudinal Flight Path Control Margins - STOL Landing

The speed and angle of attack margins throughout a flare and landing shall be at least those given in Table D for a flare from any allowable approach condition on glide slope to a touchdown point 30% down the minimum certified field length.

TABLE D

MARGINS	
Speed Margin Above Minimum Speed	?
Angle of Attack Margin Below Loss of Control, Abrupt Stall and Maximum Demonstrated Angle of Attack	?

C. GO-AROUND

The results of the go-around tests from the AWJSRA and BR 941S studies have not revealed any characteristics of STOL's that could not be found in conventional aircraft. There are two aspects of STOL's which might require special consideration however. The first of these relates to the degree of reconfiguration allowable for a go-around and the other is the OEI performance which must be expected, especially in terms of descent below go-around initiation height.

A STOL airplane flying a relatively steep glide slope with sufficient additional down correction capability must operate at a relatively low lift/drag ratio. To provide for an adequate OEI climb capability in such a high drag configuration might easily require an inordinate OEI thrust/weight ratio. The EBF design study of Reference 12 demonstrates the strong impact of OEI go-around performance criteria on aircraft thrust/weight ratio and gross weight. Thus, provision for allowing a configuration change should receive consideration.*

Both the BR 941S and the AWJSRA simulator models required a configuration change for OEI go-arounds. (In fact, the BR 941S with transparency required a configuration change with AEO.) These two aircraft represented extremes in ease of reconfiguration. The BR 941S employed a thumb switch on the throttle which both removed transparency and partially retracted flaps. Thus reconfiguration was efficiently executed in the same motion that added power. Such a scheme was clearly acceptable to the subject pilots. At the other extreme the AWJSRA simulation required a series of carefully executed steps to reconfigure and establish an OEI go-around. Following application of full throttle the flap handle had to be repositioned to an intermediate setting (without the aid of a gate) and the nozzle lever had to be repositioned to full forward. The latter step required some degree of finesse to avoid excessive lateral-directional transients from the asymmetric nozzle thrust vector. This situation created an excessive workload and pilots elected to use the right seat occupant to reset flaps. It was one pilot's view that use of an additional person had a direct bearing on overall go-around performance for this aircraft.

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* The design results of Reference 12 assume a flap change is allowed for an OEI go-around.

Our recommendation remains the same as previously given in Reference 1: It seems reasonable to allow at least one configuration change for go-arounds (i.e., one manipulator motion) if it is as easy to accomplish as for the BR 941S. Increased complexity in reconfiguration could be acceptable subject to consideration of factors such as:

- Number of separate manipulator motions required
- Requirement to move manipulators in a specific order
- Need to visually position manipulators
- Attitude transients (lateral-directional or longitudinal) excited by reconfiguration
- Need of aid from other crew members to reposition manipulators or monitor status.

The second aspect of STOL go-arounds worth mentioning is the large loss of altitude which can be expected following go-around initiation with OEI. Four factors play a role in altitude loss:

- Approach rate of descent
- Maximum OEI rate of climb
- Time required to reconfigure
- Flight path bandwidth.

Each of these tends to be unfavorable for STOL aircraft. The average altitude loss demonstrated by the AWJSRA (which was capable of a climb angle in excess of 4 deg) was greater than 100 ft below decision height. This feature of performance should perhaps be considered with respect to airworthiness as well as definition of IFR minimums.

In order to govern altitude loss following go-around initiation, at least two approaches may be taken. The first is to simply limit altitude loss directly. The second is to do so indirectly by limiting the response time from approach rate of descent to go-around rate of climb. (i.e., the effective flight path bandwidth including configuration change effects.) Since altitude is an easy quantity to measure there does not appear to be any reason to take the indirect approach. One possible way of stating an airworthiness standard on altitude loss is:

• --- Go-Around Performance - Altitude Loss

With the aircraft trimmed for any combination of the allowable approach conditions, the altitude loss following go-around initiation with simultaneous loss of power must not be greater than 100 ft.

This is a short-term flight path control power constraint. A long-term constraint is also required, namely, a steady-state OEI climb requirement. A simple climb gradient is probably sufficient.

D. TAKEOFF

Takeoff characteristics of the BR 941S and AWJSRA simulator models were largely representative of conventional aircraft. Current FAR Part 25 airworthiness standards should prove adequate and could probably be simplified. Both aircraft simulation models were forgiving of abuses in V_R and V_2. There were no significant problems with engine failures in winds and turbulence. The one OEI control problem noted for the AWJSRA was lack of directional control following engine failures below 30 kt. At these speeds the rudder was not powerful enough to overcome the asymmetric thrust and the aircraft would drift laterally off the runway. However, even this problem would be adequately covered by FAR Part 25.

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APPENDIX

FLIGHT PATH CRITERIA FROM OTHER SOURCES

This Appendix provides a tie to related STOL airworthiness efforts. Some of the configurations tested in the BR 941S and AWJSRA simulations are presented in terms of other suggested airworthiness criteria. The specific configuration cases given border on being unacceptable. Specific pilot ratings and comments can be found in respective data analysis volumes. The other airworthiness criteria included here come from:

- FAR Part 25 (Reference 7)
- Special Conditions to FAR Part 25 for BR 941 (Reference 9)
- NASA TN D-5594 (Reference 4)
- NASA CR-114454 (Reference 6)
- AGARD R-577-70 (Reference 5)

These criteria are arranged in tabular form.

Table A-1 contains criteria which are aimed at setting a minimum approach speed. In each case the criteria are set relative to a margin above a particular minimum speed. There is really no consistent pattern for even these two example aircraft. Further, the analysis of Volume II shows that for a given approach speed, other variables such as steady-state wind condition or glide slope angle can have an effect equivalent to varying airspeed. It was for such reasons that a more general approach was taken in this study. Rather than just a speed margin, minimum approach speed criteria proposed here are based on specific control characteristics. Speed (and angle of attack) margins are included only to guard against conditions involving severe or complete loss of control.

Table A-2 presents load factor criteria. In general, these requirements represent the attempt to provide some guaranteed level of flight path dynamics. The Δn_z criteria are essentially equivalent to high frequency control power while the time constants (rise times) for n_z and $\dot{h}$ are equivalent to bandwidth requirements.

TABLE A-1

MINIMUM APPROACH SPEED CRITERIA

SOURCE	CRITERION	BR 941S (δ_f = 95 deg)				AWJSRA (δ_f = 65, δ_ν = 75)	
		WITH TRANSPARENCY		WITHOUT TRANSPARENCY			
		60 kt	65 kt	60 kt	65 kt	60 kt	65 kt
FAR Part 25	>1.3 V_s (flight idle power)	0.97 V_s	1.05 V_s	1.01 V_s	1.09 V_s	.78 $V_{s_{\text{"1g"}}}$	.84 $V_{s_{\text{"1g"}}}$
Breguet Special Condition NASA TN D-5594 NASA CR-114454	>1.15 V_{min} AEO and approach power	1.06 V_{min}	1.15 V_{min}	1.06 V_{min}	1.15 V_{min}	1.24 V_{min}	1.33 V_{min}
Breguet Special Conditions	>1.3 V_{min} OEI and maximum power	1.14 V_{min}	1.23 V_{min}	1.30 V_{min}	1.40 V_{min}	1.13 V_{min}	1.22 V_{min}
NASA TN D-5594	>1.15 V_{min} OEI and maximum power	1.14 V_{min}	1.23 V_{min}	1.30 V_{min}	1.40 V_{min}	1.13 V_{min}	1.22 V_{min}
NASA CR-114454	Step vertical gust to stall wing > 20 kt OEI	8.0	12.2	7.8	12.5	10	10

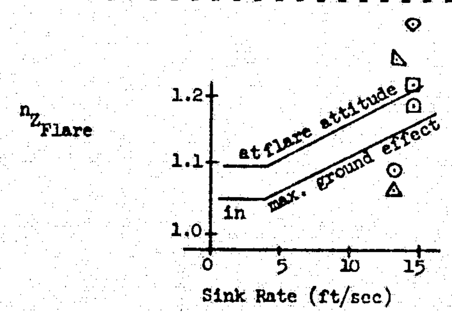
V_{min} for BR 941S and AWJSRA is assumed to be minimum possible speed at given power setting;

$$\left(\frac{\partial\gamma}{\partial V}\right)_T = \infty \text{ at } V_{min}$$

TABLE A-2

LOAD FACTOR CRITERIA

SOURCE	CRITERION	BR 941S (δ_f = 95 deg) T in 60 kt	BR 941S T in 65 kt	BR 941S T out 60 kt	BR 941S T out 65 kt	Augmentor Wing 60 kt	Augmentor Wing 65 kt
Breguet Special Conditions	$\Delta n_z > .25$ g AEO, approach power, elevator input	.10	.22	.07	.19	.26	.31
NASA CR 114454	$\Delta n_z > .35$ g AEO, approach power, elevator input	.10	.22	.07	.19	.26	.31
	$\Delta n_z > .5$ g AEO, maximum power, elevator and throttle inputs	.29	.43	.40	.52	.58	.66
NASA TN D-5594 AGARD R-577-70	When maximum $\Delta n_z < .15$ g with elevator alone	Maximum Δn_z: .15	na	.19	na	na	na
	$\Delta n_z = \pm .1$ g in 0.5 sec for throttle input at constant attitude	Time to $\Delta n_z = .1$: 1.1	na	1.0	na	na	na
	When maximum Δn_z is .15 - .3 g with elevator alone: Δn_z for AEO maximum power throttle input	Maximum Δn_z: na	.16	na	.18	.35	.38
	$\Delta n_z = \pm .1$ g in 1.5 sec for throttle input at constant attitude	Time to $\Delta n_z = .1$: na	1.2	na	1.1	.4	.4
NASA CR 114454	$\tau_{n_z} < 1$ sec τ_{n_z} is time from flight path input until n_z reaches 63% of first peak	1.6	1.3	1.3	not measured	.5	.6
	$\tau_{\dot{h}} < 0.8$ sec $\tau_{\dot{h}}$ is time to achieve a positive change in vertical speed following a climb command	1.4	1.0	1.2	not measured	.8	.7
	n_z available at stall warning shall not be less than values shown in figure to the right. Requirement applies at approach speed and thrust not exceeding that required for constant speed in the flare.	Data are for free air and constant thrust Symbols ⊙	⊡	△	◘	◺	◇



The criteria of Table A-3 are referred to as flight path criteria. In general, these are steady-state characteristics with the exception of n_z/α which is high frequency attitude control sensitivity. The $\Delta\gamma$ requirement is long-term flight path control power while $\frac{\partial\gamma}{\partial V}$ partially defines long-term cross-coupling as does effective thrust vector angle.

Table A-4 relates the various criteria of the preceding tables in terms of the general flight path control classification scheme of Section III.

Relative to go-around, Table A-5 gives the steady-state AEO and OEI climb performance for the simulation models used here with and without reconfiguration.

TABLE A-3

FLIGHT PATH CONTROL CRITERIA

SOURCE	CRITERION	BR 941S (δ_f = 95 deg)				Augmentor Wing	
		T in		T out			
		60 kt	65 kt	60 kt	65 kt	60 kt	65 kt
NASA TN D-5594 NASA CR 114454	For altitude <1000 ft, rate of descent <1000 fpm	794	860	794	860	794	860
Breguet Special Conditions	$\Delta\gamma = \pm 2$ deg (assumed constant airspeed)	+7 -5	+7.5 -8	+12.4 -2	+13 -3.8	11.9 -5.8	11.7 -6.3
NASA TN D-5594 AGARD R-577-70	$\Delta\gamma = -2$ deg (constant attitude)	-9	-8.5	-4	-3.5	-6.8	-6.8
NASA CR 114454	$\Delta\gamma = -2$ deg at V_{APP} + 10 kt	-8	-7.5	-3.5	-4	-6.9	-7.6
	$\Delta\gamma = \Delta\gamma_{STILL\ AIR} + \Delta\gamma_{HEADWIND}$						
		CRITERION $\Delta\gamma$					
	$\Delta\gamma_{STILL\ AIR}$ is greater of: a) +2 deg at V_{APP} -10 kt b) $20\left(\frac{\partial\gamma}{\partial V}\right)_T$ at V_{APP}	7.4	5.5	8.2	5.5	6.95	5.5
		941 $\Delta\gamma$				Augmentor Wing $\Delta\gamma$	
	$\Delta\gamma_{HEADWIND} = -\gamma_{APP} \frac{V_{DESIGN\ WIND}}{V_{APP}}$ (assumes $V_{DESIGN\ WIND}$ = 30 kt)	7 at V_{APP}	6.2 at V_{APP} -10	12.4 at V_{APP}	11 at V_{APP} -10	11.9 at V_{APP}	11.7 at V_{APP} -10
	For STOL piloting technique (throttle controls flight path & pitch attitude controls airspeed): $n_z/\alpha > 0$ g/deg	.025	.039	.019	.031	.025	.030
	$\left(\frac{\partial\gamma}{\partial V}\right)_T < 0.2$ deg/kt	.18	.079	.24	.034	.16	.057
	$\left(\frac{\partial\theta}{\partial\gamma}\right)_V$ limit unknown; negative values undesirable but allowable	-.040	.24	-.54	-.015	-.72	-.563
	$-.6\ \text{deg/kt} < \left(\frac{\partial\theta}{\partial V}\right)_\gamma < 0$	-.62	-.43	-.85	-.68	-.34	-.486
	Effective thrust vector angle, limits unknown, 13 - 90 deg suggested	80.3	80.5	81.6	76.9	90.9	89.6

TABLE A-4

RELATIONSHIP OF VARIOUS CONTROL CRITERIA

CHARACTERISTIC	SOURCE	SHORT TERM (High Frequency)	LONG TERM (Low Frequency or Steady State)
Control Sensitivity	OTHER	• $n_z/\alpha \left(= \frac{\partial n_z}{\partial \alpha} \right)$	• $\frac{\partial \theta}{\partial \gamma}$ • $\frac{\partial \theta}{\partial V}$
	SECTION III	• $\frac{\partial n}{\partial \delta_T}$ (throttle control) • $\frac{\partial n}{\partial \alpha}$ (attitude control)	No criteria considered necessary
Control Power	OTHER	• Δn_z • Δn_z within a specified time	• $\pm \Delta\gamma$ or $-\Delta\gamma$ • Maximum rate of descent
	SECTION III	• $\pm \Delta\gamma$ in a specified time • $\Delta\dot{h}$ sustained during flare	• $\pm \Delta\gamma$
Control Bandwidth	OTHER	• τ_{n_z} • $\tau_{\dot{h}}$	
	SECTION III	• ω_{BW} for G/S error ($\sim$ altitude)	For all practical purposes, no low frequency bandwidth limit should exist in presence of other constraints.
Control Cross-Coupling	OTHER		• $\left.\frac{\partial \gamma}{\partial V}\right\vert_{\delta_T}$ • Thrust vector angle
	SECTION III	• $\mu_{.3}^{STOL}$	• μ_{0}^{STOL}

TABLE A-5

GO-AROUND PERFORMANCE

Climb Gradient, Rate of Climb (fpm)

Engine Status	Breguet 941S					Augmentor Wing		
	Flap (deg)	Transparency In		Transparency Out		Flap (deg)		
		60 kt	65 kt	60 kt	65 kt		60 kt	65 kt
AEO	95*	-.009, -55	0 , 0	.084, 509	.096, 629	65*	.077, 466	.073, 482
OEI	95*	-.065, -394	-.059, -388	.012, 73	.021, 138	65*	-.011, -70	-.003, -20
AEO	70	.149, 899	.140, 913	.163, 978	.156, 1015	30	.339, 1953	.353, 2194
OEI	70	.075, 455	.070, 460	.089, 539	.086, 564	30	.042, 254	.061, 402

*Approach flap setting.